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Assessing the drought mitigation ability of the reservoir in the downstream of the Yellow River

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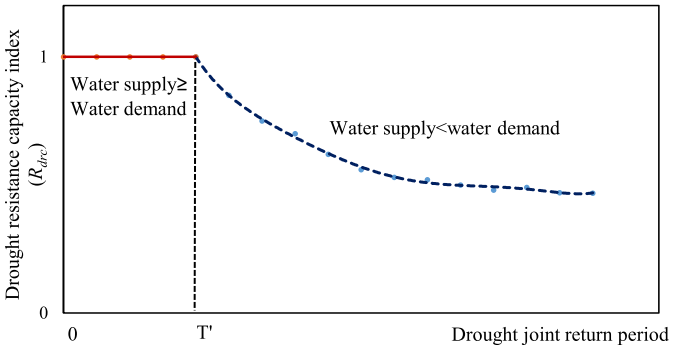
HIGHLIGHTS

- Drought adaptation and resistance capacity are chosen as two drought mitigation ability metrics.
- Drought adaptation capacity reflects reservoir scale, layout rationality and management.
- Drought resistance capacity reflects water supply guarantee rate under a given return period.
- Drought problems is worsening in the downstream of Yellow River.
- Drought adaptation and resistance capacity in the downstream of Yellow River need to be improved.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to climate change and human activities, drought frequency and its corresponding impact have intensified in many regions across China. Reservoirs are key in regulating streamflow and mitigating a drought's impact. Therefore, it is vital to analyze their drought mitigation ability. In this study, the drought adaptation capacity and drought resistance capacity of the reservoir are selected as two drought mitigation ability metrics to measure the effectiveness of a reservoir when facing a drought. The drought adaptation capacity represents the ability of a reservoir to prevent and mitigate damage caused by drought. It is assessed from two viewpoints, one reflecting the reservoir scale and layout reasonability, while the second reflecting the engineering operation and management. The drought resistance capacity refers to the ability of a reservoir to meet the water demand under a certain level of a drought (i.e. drought joint return period, which is defined later), and is calculated based on the reservoir's water supply and water demand. These two drought mitigation ability metrics can be applied not only for a single reservoir, but also for a group of reservoirs. This study applies these two metrics in the downstream of the Yellow River for a group of reservoirs. The results show that: 1) the ability of reservoirs in the downstream of the Yellow River for prevention and mitigation of damage caused by drought rates in the normal grade; and 2) the reservoirs can better resist the drought whose joint return period is smaller than 2 years while the drought resistance capacity is weak when the joint return period is over 6 years. Overall, the basin's drought adaptation and resistance capacity need to be improved. Management and operation of current water conservancy projects still need to be enhanced.

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1. Introduction

Global warming and a rapid increase in water demand have intensified drought frequency in many regions (Kim et al., 2015; Jump et al.,

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2017; Wang et al., 2017). As a result, a lot of reservoirs have been constructed to better allocate, regulate, and store water resources, and reduce the variability of natural streamflow (Peisert and Sternfeld, 2005). Since limited research exists that evaluates the drought mitigation ability of the reservoir, the main purpose of this study is to assess the drought adaptation capacity and drought resistance capacity of the reservoir. These two drought mitigation ability metrics can relatively reflect the effectiveness of a reservoir when facing a drought. This assessment contributes to future project construction, as well as drought relief policy making.

Drought adaptation capacity refers to the ability of a reservoir to prevent and mitigate damage caused by drought (Wang et al., 2015). To better analyze drought adaptation capacity from all aspects, in this study, ten drought adaptation capacity evaluation indices are selected (Wang et al., 2015). These ten indices can be divided into two groups. One group composed of four indices is related to the reservoir scale and layout reasonability, and could reflect the reasonability of engineering construction (Xu et al., 2004). The second composed of six indices is related to reservoir operation and management (Karamouz and Araghinejad, 2008; Daneshmand et al., 2014).

There may be deviations among drought adaptation capacity analyses based on different evaluation indices. To synthesize multiple evaluation indices into a comprehensive index, a weighting scheme is needed (Svoboda et al., 2002; Rajsekhar et al., 2015). Numerous weighting schemes have been widely utilized. Weighting schemes can be divided into three categories: subjective, objective, and combinatory (Liu et al., 2015). A subjective weighting scheme determines weights according to experts from their extensive experience (Kurttila et al., 2000). This method is very subjective and the results can vary strongly between experts. Weights of the objective weighting scheme are determined by the relationship among original data. This method has an advantage on the basis of mathematical theory (Delgado and Romero, 2016). However, the weights may be inconsistent with subjective weights. And the least important index in reality may also have the maximum weight. A combination weighting scheme integrates subjective and objective weights to better combine the preferences of policy makers and reduce subjective randomness (Liu et al., 2015). In this study, the Delphi method (Dalkey and Helmer, 1963) combined with the analytic hierarchy process (AHP) (Ying et al., 2007) were chosen to obtain the subjective weights while the entropy weighting scheme (Liu et al., 2015) was chosen to acquire the objective weights. Then, the combination weighting scheme was employed to gain reliable weights of multiple evaluation indices by combining subjective and objective weights.

The drought resistance capacity represents the ability of a reservoir to meet the water demand under a certain level of a drought (i.e. drought return period) (Liang et al., 2013). In this study, a drought resistance capacity index was used to measure the water supply guarantee rate. It refers to the ratio between reservoir's water supply and water demand which further reflects the reservoir regulation capacity and resistance capacity when facing a drought (Liang et al., 2013). Drought impacts have multiple characteristics such as drought duration, peak, and severity (Yang et al., 2018). In this study, the drought joint return period, which is computed by a copulas function as the basis for the drought resistance capacity calculation, considers two drought characteristics: drought duration and severity to better reflect complex drought characteristics (Yang et al., 2018). To identify these two characteristics, an accurate drought index is essential (Mathbout et al., 2018). Most drought indices mainly reflect one type of drought (meteorological, hydrological, agricultural, or socioeconomic drought) (Rajsekhar et al., 2015). To simultaneously react to different types of droughts, a multiple drought index (MDI) is constructed by integrating meteorological, hydrological, and agricultural drought indices through principal component analysis (Keyantash and Dracup, 2004). This multiple drought index can better represent varied drought factors' impact on actual drought conditions (precipitation, evaporation, streamflow, and soil moisture) (Meyer et al., 1991; Keyantash and Dracup, 2004; Yang et al., 2018).

The paper is organized as follows: Section 2 states the study area and date needed. Section 3 describes the process of using the combination weighting scheme to analyze drought adaptation capacity of the reservoir, and the process of constructing a multiple drought index for further evaluating the drought resistance capacity of the reservoir. Section 4 provides the results, and Section 5 concludes the paper.

2. Study area and data

2.1. Study area

Recently, China has experienced many severe droughts, especially in the Yellow River Basin. The Yellow River is known as China's mother river, and it plays a powerful role in China's economy. It is the second longest river in China and the fifth longest river in the world (Feng et al., 2012). Its geographic location in longitude and latitude extend from 95°53′ to 119°05′, and 32°10′ to 42°50′, respectively. The basin area is about 7.5×10^5 km^2. It flows through nine provinces (Qinghai, Sichuan, Gansu, Ningxia, Neimenggu, Shaanxi, Shanxi, Henan, and Shandong) before depositing into the Bohai Sea (Feng et al., 2012). However, the increasingly severe drought situation has hindered sustainable development in the Yellow River Basin. Therefore, it is vital to assess the drought adaptation and resistance capacity of constructed water conservancy projects.

According to the Yellow River Water Resources Bulletin, this river basin is divided into 8 partitions (Fig. 1). In this study, the downstream of the Yellow River was selected as the study area. The study area is composed of two partitions: Sanmenxia to Huayuankou Partition and Downstream of Huayuankou Partition.

2.2. Data

The data employed in this study contains meteorological data, hydrological data, socio-economic data, and reservoir characteristics. Monthly meteorological data from 1960 to 2013 in each meteorological station was collected from the China Meteorological Data Service Center. The data principally includes precipitation, temperature, sunshine duration, and humidity. Monthly hydrological data (streamflow) was gathered from hydrological stations. Other socio-economic data was mainly gathered from the Yellow River Water Resources Bulletin, the National Bureau of Statistics of the People's Republic of China, the Statistical Yearbook of China, and the Statistical Communique of Social Development. Monthly water demand was calculated according to the National Integrated Water Resources Planning Technical Details. Total water demand includes urban, industrial, agricultural, and ecological water demand, and were mainly calculated by the quota method. In this study, an optimization operation model of the reservoir system in the downstream of the Yellow River was first constructed. The objective function of the model is the minimum water deficit. Main constraints mainly contain the water balance, water level, and power output capacity. Then based on the streamflow data, monthly reservoir water supply can be acquired by solving the model. The node diagram of the reservoir system in the downstream of the Yellow River is given in Fig. 2. Fig. 2 shows that, in this study, the drought adaptation and resistance capacity are assessed based on six reservoirs i.e. Xiaolangdi, Xixiayuan, Guxian, Luhun, Xuye, and Dongpinghu. Xiaolangdi and Xixiayuan are located in the main stream of the Yellow River Basin. Among these six reservoirs, the Xiaolangdi has the largest storage capacity. It presents a stronger guarantee for water supply in the downstream of the Yellow River.

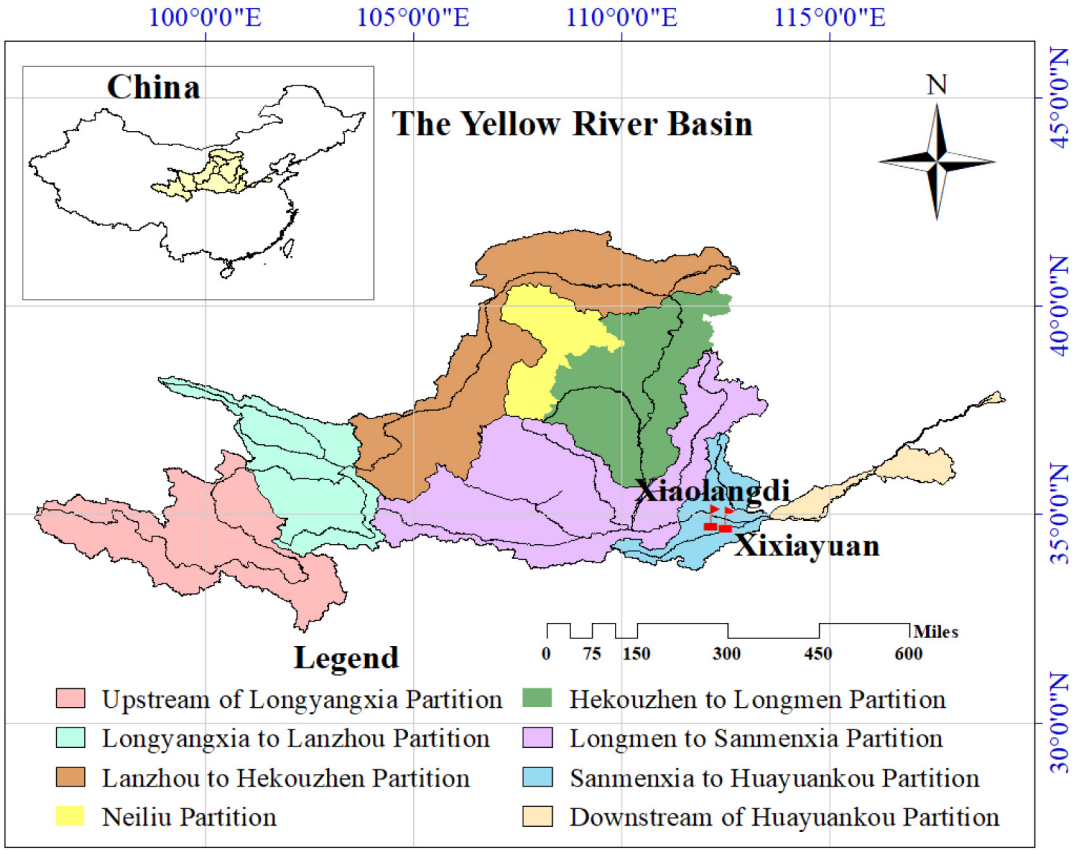

Fig. 1. Sketch map of Yellow River partitions.

3. Methodology

3.1. Drought joint return period calculation by a multiple drought index (MDI)

In this study, four single drought indices were employed to construct a multiple drought index (MDI) that can reflect multiple drought factors (precipitation, evaporation, streamflow, and soil moisture) at the same time. These four drought indices include standardized precipitation index (SPI) (McKee et al., 1993), standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010), streamflow drought index (SDI) (Nalbantis and Tsakiris, 2009), and the Palmer drought severity index (PDSI) (Palmer, 1965). The monthly basin's meteorological data was calculated based on the Thiessen Polygon. Then monthly SPI, SPEI, and PDSI drought indices values were calculated according to the basin's meteorological data. In the study region, the monthly basin's hydrological data was collected from the Huayuankou hydrological station, based on which, the monthly SDI drought index values were calculated. After that, the multiple drought index (MDI) was constructed according to the four monthly drought indices values and the principal component analysis (PCA) (Keyantash and Dracup, 2004). The calculation process is shown as follows.

(1) Original data input

The input data is a matrix ($f \times p$, where f is the number of samples and p is the number of variables). In this study, as four single drought

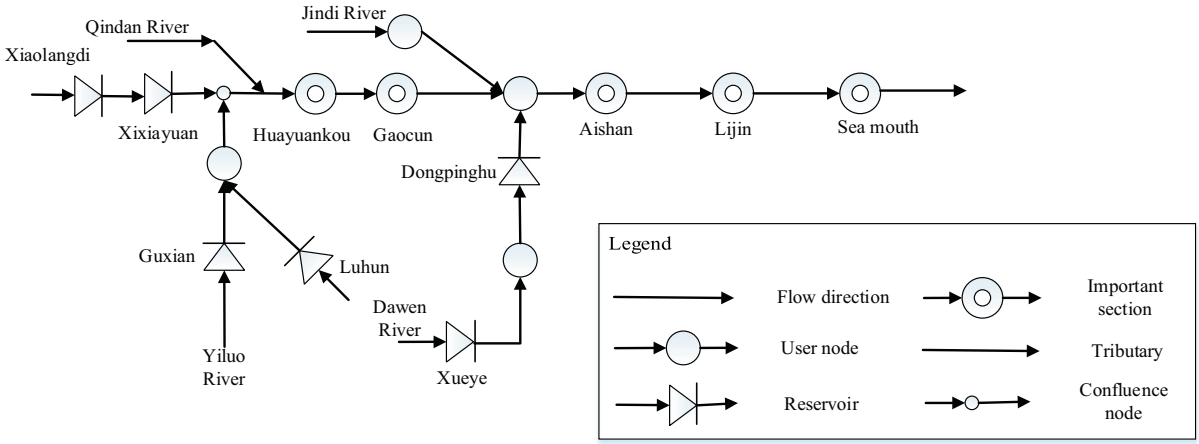

Fig. 2. Node diagram of reservoirs in the downstream of the Yellow River.

indices and monthly data from 1960 to 2013 were employed, $f = 54$ (years) × 12(months) = 648 and $p = 4$. Then, the correlation matrix R ($p \times p$) was computed by analyzing the correlations among p variables.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1p} \\ r_{21} & r_{22} & \cdots & r_{2p} \\ \vdots & \vdots & \vdots & \vdots \\ r_{p1} & r_{p2} & \cdots & r_{pp} \end{bmatrix} \quad (1)$$

$$r_{ij} = \frac{\sum_{k=1}^{n}(x_{ki}-\overline{x_i})(x_{kj}-\overline{x_j})}{\sqrt{\sum_{k=1}^{n}(x_{ki}-\overline{x_i})^2 \sum_{k=1}^{n}(x_{kj}-\overline{x_j})^2}} \quad (i,j = 1,2,\cdots,p) \quad (2)$$

(2) Principal components calculation

After that, eigenvalue λ_i ($i = 1,2,\cdots,p$) of correlation matrix R was computed, and λ_i was sorted from big to small (i.e. $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_p \geq 0$). Next, eigenvector e_i corresponding to λ_i was calculated. The contribution of each principal component (D_i) is shown as follows.

$$con_i = \frac{\lambda_i}{\sum_{d=1}^{p}\lambda_d} \quad (3)$$

$$D_i = Xe_i \quad (4)$$

where con_i is the contribution of the principal component.

(3) Selection of principal components to construct the multiple drought index (MDI)

In this study, k principal components were selected whose total contributions were over 80% ($k \leq p$). The equation of the multiple drought index (MDI) is shown as follows.

$$MDI = \sum_{i=1}^{k}\omega_i D_i \quad (5)$$

$$D_i = a_{i1}PDSI + a_{i2}SPEI + a_{i3}SDI + a_{i4}SPI \quad (6)$$

$$\omega_i = \frac{g_i}{\sum_{i=1}^{k} g_i} \quad (7)$$

where ω_i is the weight of principal component (D_i) to construct the MDI; a_i represents the eigenvector; and g_i refers to the contribution of principal component (D_i);

Based on the constructed multiple drought index (MDI), drought events incorporating two drought characteristics: drought duration (D) and drought severity (S), were identified according to runs theory (Yevjevich, 1967). Afterwards, the best fit marginal distribution functions (candidates covering Gamma, Weibull, Normal, Exponential, Poisson, Rayleigh and Log-normal) of drought duration and drought severity were selected based on minimum *RMSE* values between univariate empirical and theoretical cumulative probability (Yang et al., 2018). The univariate theoretical cumulative probability was calculated by the distribution function while empirical cumulative probability (P_e) was calculated as follows:

$$P_e = P(A \leq a_i) = \frac{\sum_{m=1}^{i} N_m - 0.44}{n + 0.12} \quad (8)$$

where N_m denotes the number counted as $A \leq a_i$; and n represents the total number.

Table 1
Distribution functions of bivariate Archimedean copulas.

Function	Distribution function $C(u,v)$	Scope of parameter θ
Gumbel	$e^{-[(-\ln u)^\theta+(-\ln v)^\theta]^{1/\theta}}$	$[1,\infty)$
Clayton	$\max[(u^{-\theta}+v^{-\theta}-1)^{-1/\theta},0]$	$(0,\infty)$
Frank	$-\frac{1}{\theta}\ln[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}]$	$(-\infty,+\infty)\backslash\{0\}$

Finally, the best fit copulas function (candidates including Gumbel, Clayton, or Frank) was chosen to construct the joint distribution of drought duration and drought severity also according to the minimum *RMSE* values between bivariate empirical and theoretical cumulative probability. The bivariate theoretical cumulative probability was computed by the copulas function given in Table 1 ($C(u,v)$). The bivariate empirical cumulative probability ($H(a,b)$) is displayed as follows, in Eq. (9), N_{ml} denotes the number counted as $A \leq a_i$, $B \leq b_i$.

$$H(a,b) = P(A \leq a_i, B \leq b_i) = \frac{\sum_{m=1}^{i}\sum_{l=1}^{i} N_{ml} - 0.44}{n + 0.12} \quad (9)$$

The drought joint return period was computed as follows:

$$T(d,s) = \frac{E(L)}{P(D>d \cap S>s)} = \frac{E(L)}{1 - F_D(d) - F_S(s) + F(d,s)} \quad (10)$$

where $T(d,s)$ is the drought joint return period; and $F_D(d)$ and $F_S(s)$ denote cumulative probability functions of drought duration and drought severity, respectively. $E(L)$ represents the expectation of the drought interval (Chang et al., 2016). $F(d,s)$ refers to the bivariate joint theoretical cumulative probability of drought duration and severity.

3.2. Drought adaptation capacity evaluation based on ten evaluation indices

In this study, ten drought adaptation capacity evaluation indices were chosen to reflect the characteristics of the reservoir scale and layout reasonability, as well as the reservoir operation and management in the downstream of the Yellow River (Table 2). Five grades of these ten indices are shown in Table 3 according to the drought adaptation capacity grades of Wang et al. (2015).

To synthesize ten indices into a single comprehensive index, the entropy weighting scheme was employed. In the entropy weighting scheme, entropy reflects the data disorder degree, and it is used to measure the information values. First, the drought adaptation capacity grades shown in Table 3 were normalized by the following equations to obtain the normalized matrix $U = (r_{ij})_{m\times n}$. Among ten evaluation

Table 2
Drought adaptation capacity evaluation indices.

Drought adaptation capacity evaluation indices	Group	Index symbol
Water supply capacity per unit area (10^4 m^3/km^2)	Reservoir scale and layout reasonability	A1
Reservoir storage rate (%)		A2
Effective storage per unit area (10^4 m^3/km^2)		A3
Surface water resources development and utilization rate (%)		A4
Water supply rate (%)	Engineering operation and management level	B1
Per capita irrigation area (acre)		B2
Cultivated land irrigation rate (%)		B3
Stable yield rate (%)		B4
Urban water shortage rate (%)		B5
Ecological environment water use rate (%)		B6

Table 3
Grades of drought adaptation capacity.

Drought adaptation capacity grade	Weak	Relatively weak	Normal	Relatively strong	Strong
	1	2	3	4	5
A1	≤20	(20, 30]	(30, 40]	(40, 50]	>50
A2	≤32	(32, 44]	(44, 56]	(56, 68]	>68
A3	≤2.7	(2.7, 4.7]	(4.7, 6.8]	(6.8, 8.9]	>8.9
A4	≤30	(30, 40]	(40, 50]	(50, 60]	>60
B1	≤22	(22, 40]	(40, 59]	(59, 78]	>78
B2	>1.5	(1.1, 1.5]	(0.7, 1.1]	(0.4, 0.7]	≤0.4
B3	≤27	(27, 52]	(52, 77]	(77, 90]	>90
B4	≤20	(20, 30]	(30, 50]	(50, 65]	>65
B5	>20	(15, 20]	(10, 15]	(5, 10]	≤5
B6	≤1	(1, 2]	(2, 3]	(3, 4]	>4

indices, the larger the better, the Eq. (11) is employed. The smaller the better, the Eq. (12) is employed.

$$r_{ij} = \frac{x_{ij} - \min\limits_{j}\{x_{ij}\}}{\max\limits_{j}\{x_{ij}\} - \min\limits_{j}\{x_{ij}\}} \tag{11}$$

$$r_{ij} = \frac{\max\limits_{j}\{x_{ij}\} - x_{ij}}{\max\limits_{j}\{x_{ij}\} - \min\limits_{j}\{x_{ij}\}} \tag{12}$$

where $r_{ij} \in [0,1]$, it represents the normalized value for the drought adaptation capacity grade; n is the number of evaluation indices; m is the number of drought adaptation capacity grades; and x_{ij} refers to the value shown in Table 3. The weight of each evaluation index (w_j) based on the entropy weighting scheme is shown as follows:

$$w_j = d_j / \sum_{j=1}^{n} d_j \tag{13}$$

$$d_j = 1 - e_j \tag{14}$$

$$e_j = -(1/\ln m) \sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{15}$$

$$p_{ij} = r_{ij} / \sum_{i=1}^{m} r_{ij} \tag{16}$$

Weights calculated based on the entropy weighting scheme were determined as the objective weights. They are uncorrelated with the subjective judgements of policy-makers. To better combine subjective and objective characteristics, the weights were modified according to the subjective weights:

$$q_j = \frac{\alpha_j w_j}{\sum_{i=1}^{n} \alpha_j w_j} \qquad (j = 1, 2 \ldots, n) \tag{17}$$

where q_j denotes the combinatory weight based on the combination weighting scheme, which integrated subjective and objective weight; α_j is the subjective weight. The subjective weights were calculated by the analytic hierarchy process combined with the Delphi method. This calculation process is as follows:

As two groups are considered in this study, the importance of each group (f_c) was first determined by the Delphi method; c is the number of groups. Then, all indices in one group were compared in pairs by the 1–9 scale method. The importance between two evaluation indices was determined by the Delphi method. 1, 3, 5, 7, 9 scale mean equally, weakly more, strongly more, very strongly more, and absolutely more important, respectively. 2, 4, 6, 8 reflects medial importance between adjacent scales. After that, according to the analytic hierarchy process description (Ying et al., 2007), the pairwise comparison matrix of criteria was constructed. Next, the largest eigenvalue λ_{max} of the comparison matrix and its corresponding eigenvector were calculated. The weight of each index ($W_{c1}, W_{c2}, \cdots, W_{cj}$) was also computed by the normalized eigenvector. Finally, given the weights in the two groups, the subjective weights of ten evaluation indices were calculated by the following equation:

$$\alpha_j = f_c W_{cj} \qquad (c = 1, 2) \tag{18}$$

3.3. Drought resistance capacity calculation

In this study, the drought resistance capacity index (R_{drc}) was utilized to reflect the drought resistance capacity of the reservoir when facing a drought (Liang et al., 2013). R_{drc} represents the capacity to meet the water demand under a certain level of a drought measured by the drought joint return period. It is the ratio between reservoir's water supply and water demand shown as follows:

$$R_{drc}(T) = \frac{WS(T)}{WD(T)} \tag{19}$$

where $R_{drc}(T)$, $WS(T)$, and $WD(T)$ are the drought resistance capacity index, reservoir water supply, and water demand under the drought joint return period of T, respectively. In this study, the drought resistance capacity was divided into four grades: a $R_{drc}(T)$ value less than or equal to 0.6 is defined as weak drought resistance capacity while ranges of (0.6, 0.8], (0.8, 0.9], (0.9, 1] are defined as relatively, normal, and relatively strong drought resistance capacity, respectively.

R_{drc} ranges between 0 and 1. The higher, the better the reservoir's drought resistance capacity. A R_{drc} value equal to 1 indicates that there is no water shortage, and water demand can be totally satisfied. In theory, R_{drc} declines with the increase of the drought joint return period. Fig. 3 shows the theoretical/possible drought resistance capacity index values with the changes of the joint drought return period. In Fig. 3, T' is the maximum resistible drought joint return period (i.e. the maximum drought joint return period in which drought can be totally resisted).

4. Results and discussion

4.1. Drought analysis based on the constructed multiple drought index (MDI)

Based on the monthly SPI, SPEI, PDSI, and SDI values in the study area and the principal component analysis, multiple principal components were obtained. Contributions of the first three principal components were 86.69% (over 80%). Therefore, in this study, three principal components were selected. The contribution of the first, second, and

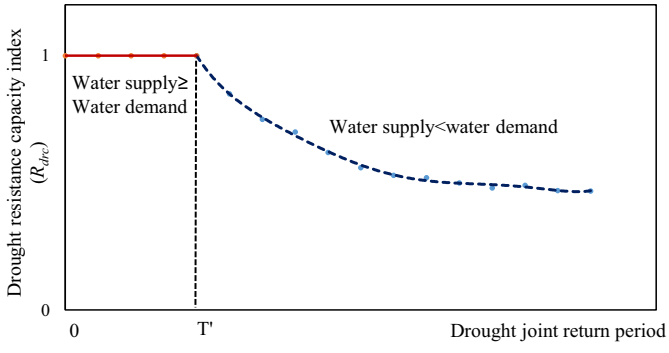

Fig. 3. Theoretical relationship between R_{drc} and the drought joint return period.

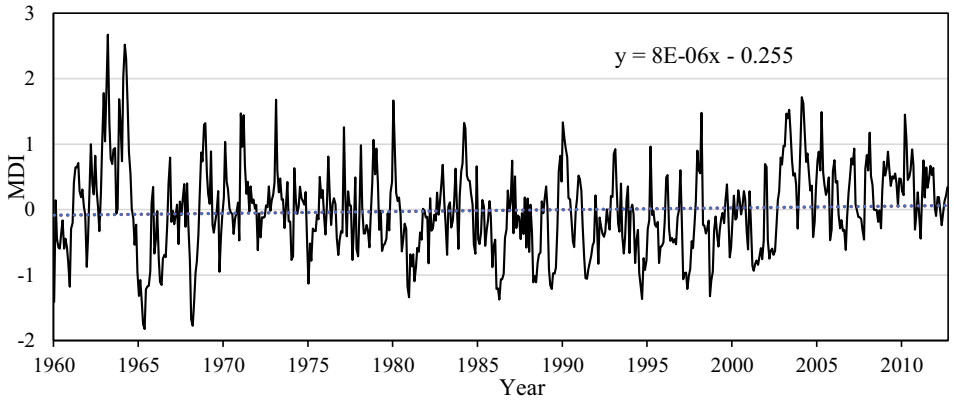

Fig. 4. Monthly multiple drought index values in the downstream of the Yellow River.

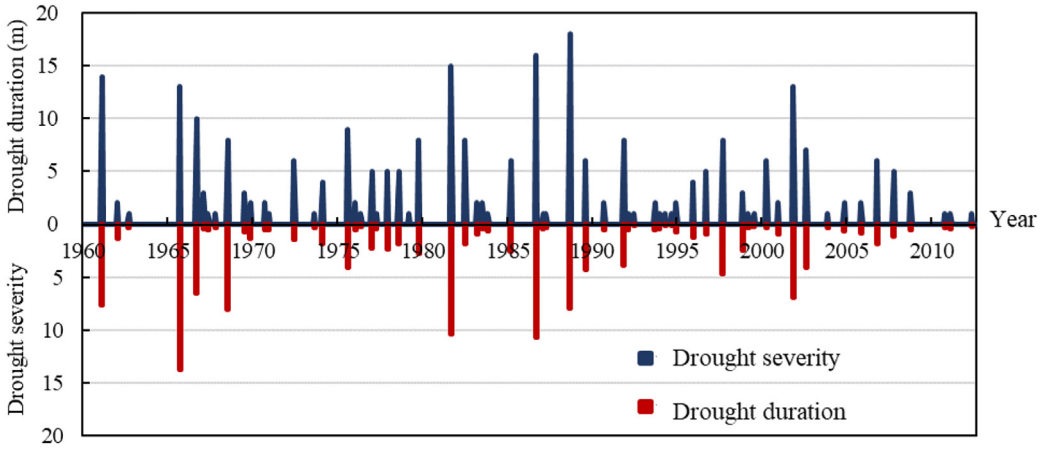

Fig. 5. Drought duration and drought severity redefined by the MDI and runs theory.

third principal component was 36.53%, 29.20, and 20.96%, respectively. According to Eq. (5) to (7), the weight of the first, second, and third principal component to construct the multiple drought index was 0.421 (36.53 % ÷ 86.69%), 0.337 (29.20 % ÷ 86.69%), and 0.242 (20.96 % ÷ 86.69%), respectively. The resulting equation for the MDI is shown below (Eq. (20)). Based on the eigenvectors for the first three principal components, the first three principal components are expressed in Eqs. (21) to (23).

$$MDI = 0.421D_1 + 0.337D_2 + 0.242D_3 \tag{20}$$

$$D_1 = -0.682808PDSI + 0.587919SPEI + 0.122352SDI + 0.404964SPI \tag{21}$$

$$D_2 = -0.023342PDSI + 0.476111SPEI + 0.780242SDI + 0.634167SPI \tag{22}$$

$$D_3 = 0.334237PDSI + 0.090320SPEI - 0.467326SDI + 0.813471SPI \tag{23}$$

Monthly MDI values from 1960 to 2013 are shown in Fig. 4. Fig. 4 shows the MDI is trending downward, indicating that the drought problem is worsening. Based on the monthly MDI values, determined drought grades, and runs theory, the drought events including two drought characteristics: drought duration and drought severity, were then redefined as illustrated in Fig. 5.

The drought events identification results in Fig. 5 are basically consistent with the recorded severe or extreme drought events (such as serious droughts in 1965, 1987, 1990, and 1997). It indicates that the MDI is relatively reliable. Results denote that the Exponential and Log-normal are the optimal marginal distribution functions to fit drought duration and severity, respectively. And the best fit copulas function to construct the joint distribution of drought duration and drought severity is the Clayton, with parameter equal to 20.8018. Based on the previously determined optimal copulas function, marginal distribution functions, and Eq. (10), the drought joint return period and corresponding contour map was computed and plotted (see in Fig. 6). The relationship between drought joint return period and two drought characteristics: drought duration and drought severity supports early drought warning.

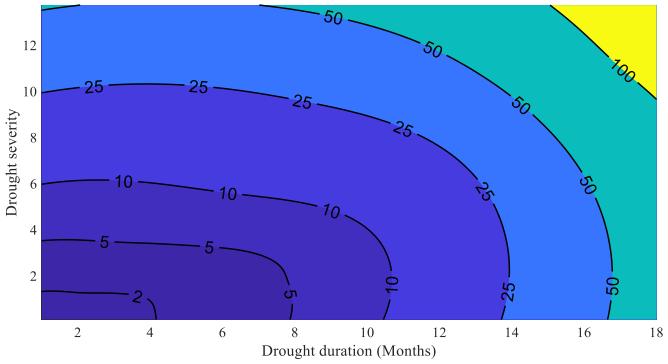

Fig. 6. Joint distribution of the drought return period.

Table 4
Importance and weights in group 1.

Group 1	A1	A2	A3	A4
A1	1	2	2	5
A2	1/2	1	1/3	5
A3	1/2	3	1	3
A4	1/5	1/5	1/3	1
Weight	0.4199	0.2092	0.2995	0.0714

Table 5
Importance and weights in group 2.

Group 2	B1	B2	B3	B4	B5	B6
B1	1	1/2	1/3	1/5	1/3	1/2
B2	2	1	1/2	1/3	1/5	3
B3	3	2	1	2	2	7
B4	5	3	1/2	1	1/2	6
B5	3	5	1/2	2	1	3
B6	2	1/3	1/7	1/6	1/3	1
Weight	0.0588	0.1047	0.3072	0.2194	0.2507	0.0592

4.2. Results of drought adaptation capacity

Based on the entropy weighting scheme, the objective weights of ten drought adaptation capacity evaluation indices (A1, A2, A3, A4, B1, B2, B3, B4, B5, and B6) were 0.0995, 0.0995, 0.1003, 0.0995, 0.1008, 0.0961, 0.0930, 0.1123, 0.0995, and 0.0995, respectively.

In this study, two groups were considered to be equally important. This is indicated by the weights of two groups as both 0.5. The pairwise comparison matrix of criteria of group 1 and 2 (determined by the Delphi method) is shown in Table 4 and Table 5, respectively. Then, based on the analytic hierarchy process, weights of four evaluation indices in group 1 and six evaluation indices in group 2 were calculated (shown in Table 4 and Table 5, respectively). In group 1, the weights of A1, A2, A3, and A4 were 0.4199, 0.2092, 0.2955, and 0.0714, respectively. In group 2, the weights of B1, B2, B3, B4, B5, and B6 were 0.0588, 0.1047, 0.3072, 0.2194, 0.2507, and 0.0592, respectively. Based on the group weights (both 0.5) and the calculated drought adaptation capacity evaluation indices' weights in each group (Table 4 and Table 5), the final subjective weights of ten evaluation weights were calculated based on Eq. (18). Final subjective weights of A1, A2, A3, A4, B1, B2, B3, B4, B5, and B6, based on the analytic hierarchy process combined with the Delphi method, were 0.2100, 0.1046, 0.1497, 0.0357, 0.0294, 0.0523, 0.1536, 0.1097, 0.1254, and 0.0296, respectively.

Then based on Eq. (17) and the calculated subjective and objective weights, the combinatory weights were computed. The combinatory weights of A1, A2, A3, A4, B1, B2, B3, B4, B5, and B6 were 0.2092, 0.1042, 0.1503, 0.0356, 0.0297, 0.0503, 0.1430, 0.1233, 0.1249, and 0.0295, respectively.

The drought adaptation capacity value was calculated by the determined combinatory weights and collected ten drought adaptation capacity evaluation indices values shown in Table 6. Table 6 shows that the drought adaptation capacity value is 3.2091. According to the grades in Table 3, the drought adaptation capacity of the reservoir is close to normal grade. Likewise, it indicates that the ability of the reservoir in the downstream of the Yellow River to prevent and mitigate damage caused by drought is in the normal grade. Nonetheless, the basin needs to improve the drought adaptation capacity of its reservoirs.

Table 7
Drought resistance capacity index analyses under different drought joint return periods.

Drought year	Drought initial month	Water demand (10^8 m^3)	Water supply (10^8 m^3)	Drought joint return period (years)	R_{drc}
1963	2	11.04	11.04	1.05	1
1970	3	36.14	29.11	2.08	0.8055
1972	6	110.15	74.38	3.30	0.6753
1991	10	114.18	62.82	7.11	0.5502
1997	7	134.11	76.62	8.78	0.5415

4.3. Results of drought resistance capacity

Based on Section 4.1, drought joint return periods were calculated. Then, according to the reservoir water supply, water demand, and Eq. (19), drought resistance capacity indices under different drought joint return periods in the study area were calculated. In this paper, only five drought resistance capacity indices' calculation process were taken as examples and are shown in Table 7. Based on the drought resistance capacity indices under different drought joint return periods, the actual relationship between the drought resistance capacity index and the drought joint return period is plotted in Fig. 7.

Fig. 7 shows that when the drought joint return period is smaller than 1 year, the R_{drc} is always 1. It indicates that the maximum resistible drought joint return period (i.e. the maximum drought joint return period in which drought can be totally resisted) is about 1 year. If the drought joint return period is smaller than 1 year, the water demand can be fully satisfied. R_{drc} decreases when drought joint return period increases. When the drought joint return period is over 2 years, the R_{drc} is smaller than 0.8. When the drought joint return period is in the range of 2 to 6 years, the R_{drc} lies between 0.6 and 0.8. When the drought joint return period is over 6 years, the R_{drc} is smaller than 0.6.

Based on the drought resistance capacity grades, when the drought joint return period is smaller than 1 year, the drought resistance capacity of the reservoir is relatively strong. When the drought joint return periods range between 1 and 2 years, and 2 to 6 years, drought resistance capacities of the reservoir are normal, and relatively weak, respectively. When the drought joint return period is over 6 years, the drought resistance capacity is weak.

Reasons for the poor drought resistance capacity in the downstream of the Yellow River are as follows: with climate change and other detrimental human activities, precipitation is showing a declining trend while water demand has increased dramatically. In addition, the Yellow River flows through Northwest China (upstream of the Yellow River) where the water shortage is severe. The vast availability of water used in this region has exerted huge pressure on the downstream, leading to a significant disparity in water supply and demand. This poor drought resistance capacity is consistent with previous results by Cai and Rosegrant (2004). They founded that the water cutoffs in the downstream of the Yellow River were very serious, and happened every year during 1972 to 1998. Additionally, the cutoff duration could last for 226 days a year, showing the relatively poor water management. All the above factors lead to the poor drought resistance capacity in the downstream of the Yellow River.

Table 6
Drought adaptation capacity analysis.

	Drought adaptation capacity evaluation index										Total
	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	
Value	4.765	3.975	5	1	3.625	2.24	1.895	2.245	1	3.995	
Weight	0.2092	0.1042	0.1503	0.0356	0.0297	0.0503	0.1430	0.1233	0.1249	0.0295	
Product	0.9968	0.4142	0.7515	0.0356	0.1077	0.1127	0.2710	0.2768	0.1249	0.1179	3.2091

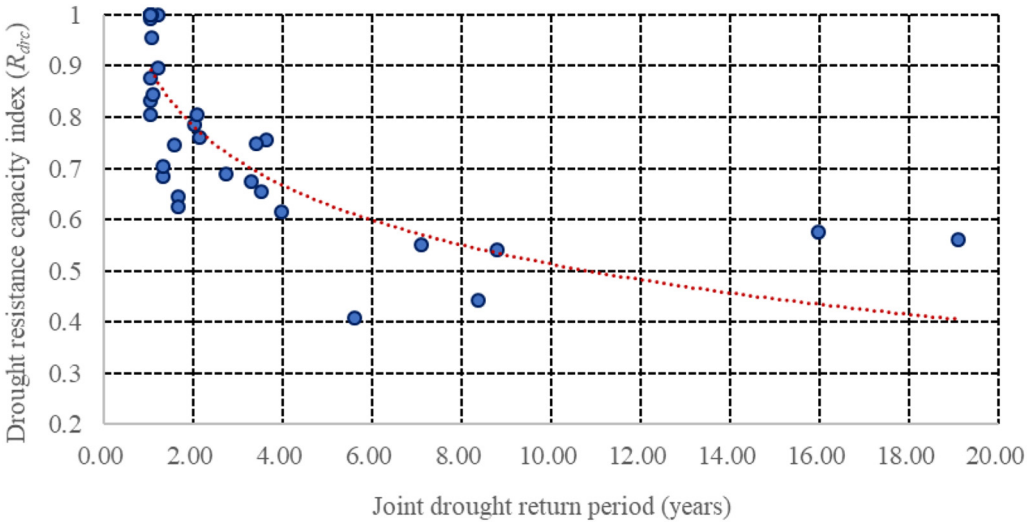

Fig. 7. Actual relationship between R_{drc} and drought joint return period.

5. Conclusions

With the rapid increase of water demand and the limited water resources, drought is an increasing problem which has hindered sustainable social and economic development in China. Construction and utilization of reservoirs are beneficial for mitigating damage caused by drought. While limited research has evaluated the drought mitigation ability of the reservoir, this study utilizes two drought mitigation ability metrics: drought adaptation and resistance capacity to reflect the basin reservoir's effectiveness when facing a drought. This study is in favor of improved water project planning and early drought policy making.

The drought adaptation capacity refers to the ability of a reservoir to prevent and mitigate damage caused by drought. In this study, ten drought adaptation capacity evaluation indices were chosen to analyze the adaptation capacity; these ten evaluation indices take engineering operation construction reasonability, engineering operation and management into consideration. Then, a combination weighting scheme was employed to synthesize ten evaluation indices into a single comprehensive index. Combinatory weights were calculated by integrating objective weights (calculated by the entropy weighting scheme) and subjective weights (computed by the analytic hierarchy process and the Delphi method). This can better reflect the preferences of policy makers and reduce subjective randomness.

The drought resistance capacity represents the ability of a reservoir to meet the water demand under a certain level of a drought. It is measured by a drought resistance capacity index (i.e. ratio of reservoir's water supply and water demand). As a drought presents multiple drought characteristics, a traditional drought return period analyzed by frequency is insufficient to reflect the complex characteristics. Therefore, in this study, the drought joint return period (considering two drought characteristics: drought duration and severity) was employed as a basis for a reasonable calculation of the drought resistance capacity of the reservoir. As a reliable drought index is essential to measure the water shortage, this study utilized a multiple (MDI) constructed by principal component analysis for better identification of drought characteristics and more reliable drought joint return period analysis.

These two metrics can be applied not only for a single reservoir, but also for a group of reservoirs. This study applies these two metrics in the downstream of the Yellow River for a group of reservoirs. The main results are as follows: (1) the drought problem is worsening in the downstream of the Yellow River, and the constructed multiple drought index (MDI) can basically capture the recorded drought event, indicating that the MDI is relatively reliable; (2) The drought adaptation capacity of reservoirs located downstream of the Yellow River is in a normal grade, which indicates the ability of reservoirs in the study area to prevent and mitigate damage caused by drought is in the normal grade; (3) the drought resistance capacity of reservoirs decreases when the drought joint return period increases. When the drought joint return period is smaller than 1 year, the drought resistance capacity of reservoirs is relatively strong. This indicates the water demand can be better satisfied in this condition. When the drought joint return period is over 6 years, the drought resistance capacity of reservoirs is relatively weak. The basin needs to improve the drought adaptation and resistance capacity of reservoirs to some extent. But only by improving the drought mitigation ability can, the water demand be better satisfied.

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